Scanner matching for standard and freeform illumination shapes using FlexRay

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ABSTRACT

IC manufacturers have a strong demand for transferring a working process from one scanner to another. Recently, a programmable illuminator (FlexRay[TM]) became available on ASML ArF immersion scanners that, besides all the parameterized source shapes of the earlier Aerial[TM] illuminator (based on diffractive optical elements) can also produce any desired freeform source shape. As a consequence, a fabrication environment may have scanners with each of the illuminator types so both FlexRay-to-Aerial and FlexRay-to-FlexRay matching is of interest. Moreover, the FlexRay illuminator itself is interesting from a matching point-of-view, as numerous degrees of freedom are added to the matching tuning space.

This paper demonstrates how the upgrade of an exposure tool from Aerial to FlexRay illuminator shows identical proximity behavior without any need for scanner tuning. Also, an assessment of the imaging correspondence between exposure tools each equipped with a FlexRay illuminator is made. Finally, for a series of use-cases where proximity differences do exist, the application of FlexRay source tuning is demonstrated. It shows an enhancement of the scanner matching capabilities, because FlexRay source tuning enables matching where traditional NA and sigma tuning are shortcoming. Moreover, it enables tuning of freeform sources where sigma tuning is not relevant. Pattern Matcher[TM] software of ASML Brion is demonstrated for the calculation of the optimized FlexRay tuned sources.

Keywords: FlexRay, freeform illumination, proximity matching, source tuning

1. INTRODUCTION

1.1 Extending the reach of ArF lithography

Lithographic research and development has reached a very interesting stage. The physical limit of water-based immersion ArF lithography has been attained with the accomplishment of full-field scanners with a numerical aperture (NA) of 1.35. Such systems have nowadays found their place in the production flow of all advanced IC manufacturers.

The gap that developed between the current optical lithography and its expected successors needs to be filled up. In view of this, a lot of effort is spent to stretch ArF immersion lithography at 1.35 NA to its application limits; e.g. double exposure/patterning schemes, litho-friendly design, alternative processing schemes using novel materials, … etc. Also, customized illumination modes are applied to improve the patterning fidelity for specific designs. When using simultaneous Source and Mask Optimization (SMO), the input is basically a given clip containing the target design, and the output of the optimization consists of an illumination source shape together with a clip containing the corresponding Optical Proximity Correction (OPC)[1]. This optimized illumination source can be a standard 'library' source shape, or, even better, a freeform source shape.

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1.2 FlexRay illuminator to provide freeform illumination

In freeform illumination, there is basically unlimited freedom in intensity and position of the light in the illumination pupil. In practice, a freeform source is often pixelated, with free choice of intensity per pixel, and smoothened by a point spread function. Similar to the traditional standard source shapes (e.g. Quasar, CQuad, Annular), freeform illumination shapes can be achieved on ASML scanners by using diffractive optical elements (DOE), which create one particular source shape[2]. The illuminator module using DOE's is referred to as Aerial™. Recently, a new programmable illuminator called FlexRay™ is presented on ASML scanners as an option which allows instantaneous and unlimited variations of standard and freeform source shapes [3,4]. Any desired change in a certain Aerial freeform source requires the fabrication of a new DOE, with a lead time of several weeks. With the FlexRay illuminator, any source adjustment can be made immediately using a Micro Mirror Array (MMA), which opens a whole new world for source tuning.

1.3 Goal of this work - Proximity matching

The OPC that is nowadays applied in low k_1 imaging involves an ever growing influence of the lithography cluster (i.e. scanner, laser, and track). As it is common practice to calibrate the OPC model using wafer prints, the final mask incorporates the proximity fingerprint of the cluster. Therefore, it is very specific, and the benefit of this Resolution Enhancement Technique (RET) optimization is partially lost when changes in the cluster occur, either over time, or by moving the production over to a different tool.

Proximity matching attempts to reduce the optical proximity differences between clusters, in order to transfer a successfully tailored RET solution from one cluster to another. By doing so, adequate proximity matching results in resist feature sizes on wafer that are closer to target and hence lead to a better use of the given critical dimension (CD) budgets[5].

In this paper, we start with an assessment of the FlexRay performance and stability. This is done by providing experimental proof for the as-is proximity agreement (i.e. not requiring any tuning) when upgrading a given scanner from Aerial to FlexRay illuminator. Also, the stability of the FlexRay sources over time, and from FlexRay to FlexRay, will be demonstrated.

Secondly, and by means of a set of examples for different use cases, this paper illustrates how freeform source tuning enhances the proximity matching capabilities with respect to traditional NA/sigma tuning as is custom practice on Aerial illuminator systems. ASML Brion's Pattern Matcher software is demonstrated as the tool for calculating the optimized freeform source.

2. FROM AERIAL TO FLEXRAY ILLUMINATOR

2.1 'As-is' proximity agreement upon illuminator upgrade from Aerial to FlexRay

In this section, it is demonstrated how the FlexRay upgrade of the illuminator on an existing scanner gives rise to unaltered imaging performance, which is a prerequisite for any IC manufacturer considering the upgrade to FlexRay illumination in order to increase the exposure tools potential.

Wafer exposures have been carried out just before and just after the installation of the FlexRay illuminator on an ASML XT:1900i. This allowed a direct comparison of the patterning behavior with an Aerial and FlexRay illuminator on one particular scanner system. Before the illuminator swap to FlexRay, hence on the Aerial illuminator, the following six illumination sources were selected:

- CQuad 30°, 1.33NA, Sigma 0.86-0.66, XY polarized
- DipoleY 35°, 1.35NA, Sigma 0.90-0.70, X polarized
- DipoleY 35°, 1.20NA, Sigma 0.73-0.53, X polarized
- Annular, 1.35NA, Sigma 0.94-0.79, XY polarized
- Freeform 1, 1.35NA, XY polarized, optimized source for 22nm node SRAM contact pattern[1]
- Freeform 2, 1.35NA, XY polarized, optimized source for 22nm node SRAM metal pattern[1]

For each of these six settings, source measurements and wafer exposures of line/space patterns through pitch were performed, before and after the replacement of the Aerial with the FlexRay illuminator. The images shown at the right side of Figure 1 are obtained using the FlexRay illuminator, and look identical to those that were obtained with the Aerial illuminator (not shown). The FlexRay illuminator was operated in the virtual DOE mode chosen in the scanner's user interface, which means that the same 'knobs' of NA and sigma are available as on the Aerial illuminator, and the source target of the FlexRay illuminator is the source that is nominally obtained from an average Aerial illuminator. In this way, ASML guarantees a smooth and user-friendly transition in operating FlexRay using standard 'library' source settings, as well as previously available customized DOE sources. In other words, and for clarity, in this work we did not use the Aerial-measured sources as freeform target for the FlexRay, but simply entered the same nominal settings on both the Aerial and FlexRay illuminator.

More important than only the source images is the printing behavior on wafer of the FlexRay compared to Aerial illuminator. For each of the six settings, mask biases were picked on a 6%attPSM mask to print vertical (V) and horizontal (H) lines to a target of 45 nm in resist through pitch, as measured using a KLA-Tencor eCD2 CD-SEM. Only for the two dipole settings, the vertical lines ('difficult' orientation for dipole Y) had a relaxed target of 55 nm in resist. No assist features were applied for any of the six exposure conditions, leading to depth-of-focus values as small as ~50 nm for the most isolated lines. After having chosen and fixed these pitch/bias combinations on the wafers exposed with Aerial, the identical same cases were measured on the wafers exposed with FlexRay. After that, the difference of the obtained proximity curves was calculated by subtracting the Aerial data from the FlexRay data, leading to six sets (V and H) of delta curves through pitch. Obviously, the goal is to have these delta curves through pitch as close as possible to zero, in which case the printing of the Aerial and FlexRay illuminators is equal. The experimentally obtained delta curves are shown in the plot in Figure 1, showing practically all delta CD's within only ±0.5 nm, i.e. for each of the six illumination conditions, for both V and H lines, from dense (pitch 80, 84, 88 nm depending on the setting) to isolated (pitch 1000 nm). This is convincing proof of the 'as-is' matching of the FlexRay to Aerial illuminator.

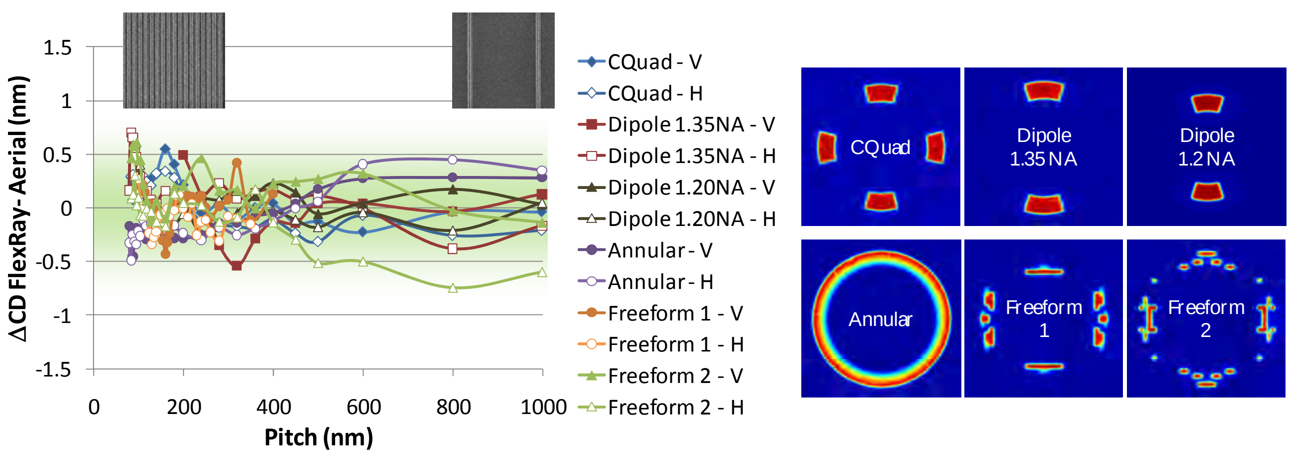

Figure 1. ASML XT:1900i before and after illuminator upgrade from Aerial to FlexRay. Experimental CD difference curves for the six settings depicted on the right, for both V and H lines through pitch. The curves are obtained by subtracting the measured proximity curves of the Aerial wafers from those obtained on the FlexRay wafers.

In addition to the line patterns through pitch, an experimental Aerial-to-FlexRay comparison of the wafer CD was made for regular contact patterns through pitch. Because of its balanced through-pitch printing behavior, a SoftQuasar setting at 1.35 NA was selected composed of a Quasar30° part with σ 0.93-0.69 and a conventional part with σ 0.42 [6]. The target in resist was chosen at 60~65nm, for pitches 120 nm to 800 nm. Similar as above, the measured proximity curve obtained by Aerial illumination is subtracted from that obtained with FlexRay illumination. The resulting delta curve is shown in Figure 2, again ranging within ±0.5 nm.

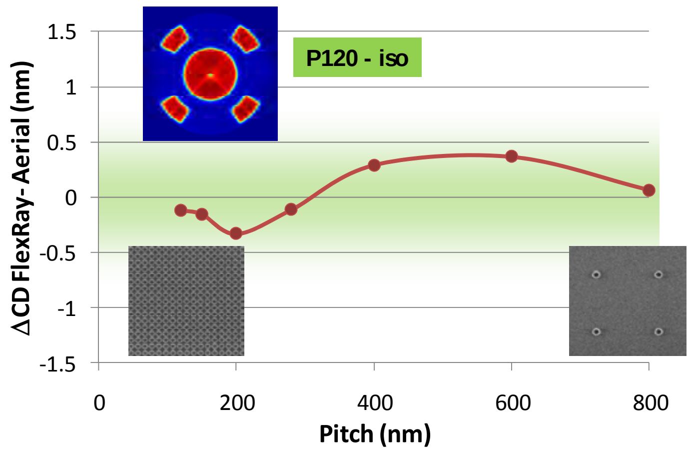

Figure 2. ASML XT:1900i before and after illuminator upgrade from Aerial to FlexRay. Experimental CD difference curve for regular contacts through pitch exposed using a SoftQuasar setting. The curve is obtained by subtracting the measured proximity curve of the Aerial wafer from that obtained on the FlexRay wafer.

These experimental findings proof the identical patterning of the Aerial and FlexRay illuminators, reassuring good continuity when upgrading to FlexRay illumination. In fact, it is fair to state that the match between Aerial and FlexRay is equally good as the reproducibility between wafers exposed with some time interval.[7]

In reference [1], a similar study is described related to the upgrade from Aerial to FlexRay. In the latter, insignificant impact on CD and process window is demonstrated for the use case of an 0.099 µm² SRAM contact pattern. More benchmarking of Aerial and FlexRay performance can be found in the references [3, 4].

2.2 Stability of the FlexRay sources over time

Now the transition of the Aerial to FlexRay illuminator has been proven, the source stability over time is to be demonstrated. To this end, source measurements for three settings are performed every couple of days, leading to three sets of ~50 measured sources in three months since the Aerial to FlexRay upgrade is performed on the above XT:1900i. These three settings are the annular setting and both freeform settings as described and depicted in Section 2.1 above.

In full analogy to the experiments above, mask CDs through pitch were determined for each illumination setting to print to 45 nm target on wafer, using the KLA-Tencor PROLITH simulator. Having fixed these mask patterns in the simulator, the proximity curves are calculated using all available sources. Finally, a reference proximity curve is subtracted, and a series of delta through pitch curves is obtained. The latter are shown in Figure 3, for the annular source (left plots), the freeform 1 source (middle plots) and the freeform 2 source (right plots), and this for vertical lines (top graphs) and horizontal lines (bottom graphs). These are the CD variations through pitch that are to be expected from the variation of the FlexRay source over time. Apart from a few points, the impact on CD appears to be limited to 0.1 nm or less for each of the considered sources.

This proves an excellent stability of the FlexRay sources over time, already from its first days of operation after installation of the illuminator. For wafer based demonstration of the stability of a scanner equipped with FlexRay, we refer to reference [7].

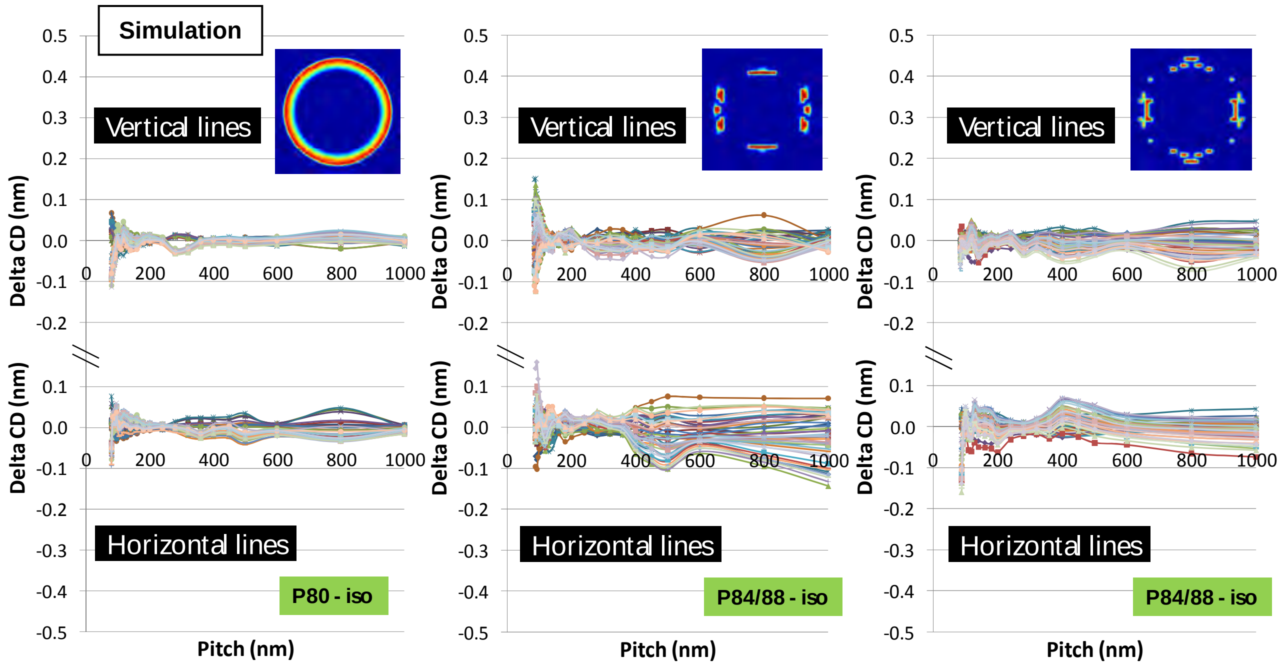

Figure 3. FlexRay source stability over time. Impact on CD through pitch, calculated with KLA-Tencor PROLITH, using sets of ~50 FlexRay source measurements, which were obtained over a 3 month period since the install of the FlexRay illuminator on an ASML XT:1900i.

2.3 Stability of the FlexRay sources from scanner to scanner

Before looking into scanner matching in the next Chapter, an evaluation is made of the equality of sources as measured on two different exposure tools both equipped with FlexRay. To this end, source measurements were collected on two tools that were individually set-up, hence without any prior matching activities. The CD difference through pitch as simulated by PROLITH using the measured sources is shown in Figure 4. The source contribution to a potential scanner mismatch is found to be at most ±0.3 nm. In other words, the illumination source will not be the *cause* of any potential scanner mismatch in the next Chapter. However, tuning of the source may well provide a *solution* to the mismatch.

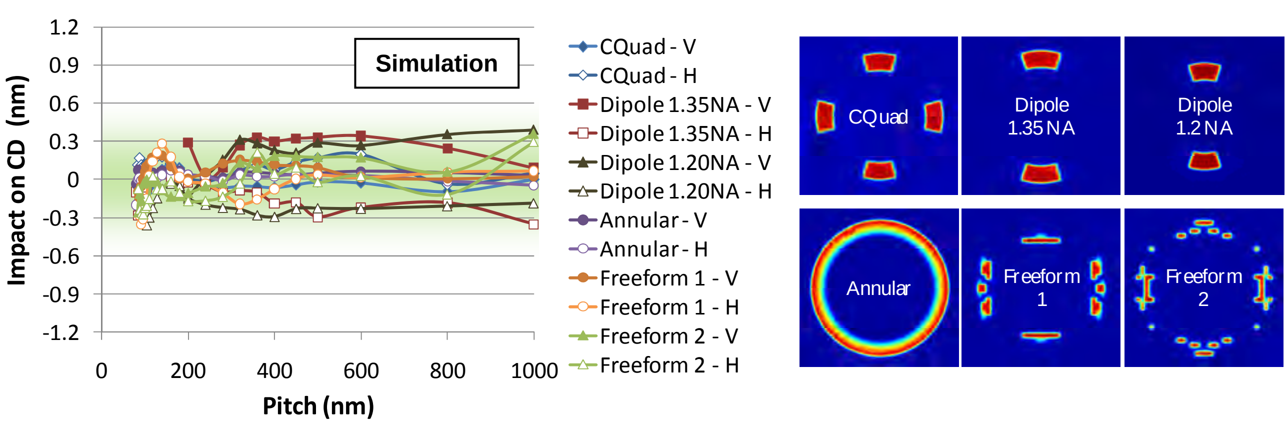

Figure 4. FlexRay source stability scanner to scanner. Impact on CD through pitch, calculated with KLA-Tencor PROLITH, using measured sources from two different exposure tools equipped with FlexRay (ASML XT III:1900Gi and XT IV:1950Hi)

3. FREEFORM SOURCE TUNING FOR ENHANCED MATCHING CAPABILITIES

3.1 ASML BRION Pattern Matcher application for freeform source tuning

In volume manufacturing there may be a need to increase the capacity of certain steps in the overall process flow. In lithography this typically means copying a process to another scanner-track combination. The actual imaging performance of this new scanner and track combination may be slightly different compared to the initial (reference) scanner-track combination. If both systems are properly calibrated and an offset between the two still exist, the ASML Brion Pattern Matcher technology can be used to bring both systems closer together in terms of imaging performance. There are different modes in which the Pattern Matcher tool can operate. In its most basic form, sensitivities are used to bring the imaging performance of the two tools together. With P as tunable scanner parameter (e.g. NA, sigma, ellipticity, focus blur), the measured delta CDs of a limited set of structures between two systems can be minimized using a least square optimization, while obeying certain scanner constraints:

$$\Delta CD = \sum_{i=1}^{i=N} \frac{\partial CD}{\partial P_i} \Delta P_i$$

With the advent of a FlexRay system, the concept of using sensitivities is no longer practical and a different optimization method is used. Instead an optimization method similar to freeform SMO is used. In such an optimization, delta CDs are compensated by making adjustments to the source by adding or removing pixels. It is clear that this approach has a much higher correction potential as compared with the scanner parameter based adjustments mentioned in the above. Since the most basic form of Pattern Matcher can use measured delta CDs and measured sensitivities, no OPC model is required. The freeform optimization flow however does require an OPC model. The use of Pattern Matcher for matching is also presented and applied in references [8,9].

In the FlexRay-based Pattern Matcher exercises further described in this paper, a set of 36 critical CDs of a reference scanner process were used to train a model. This model is then used to obtain a modified source by minimizing the measured CD differences on these critical structures. The overall flow is depicted in Figure 5.

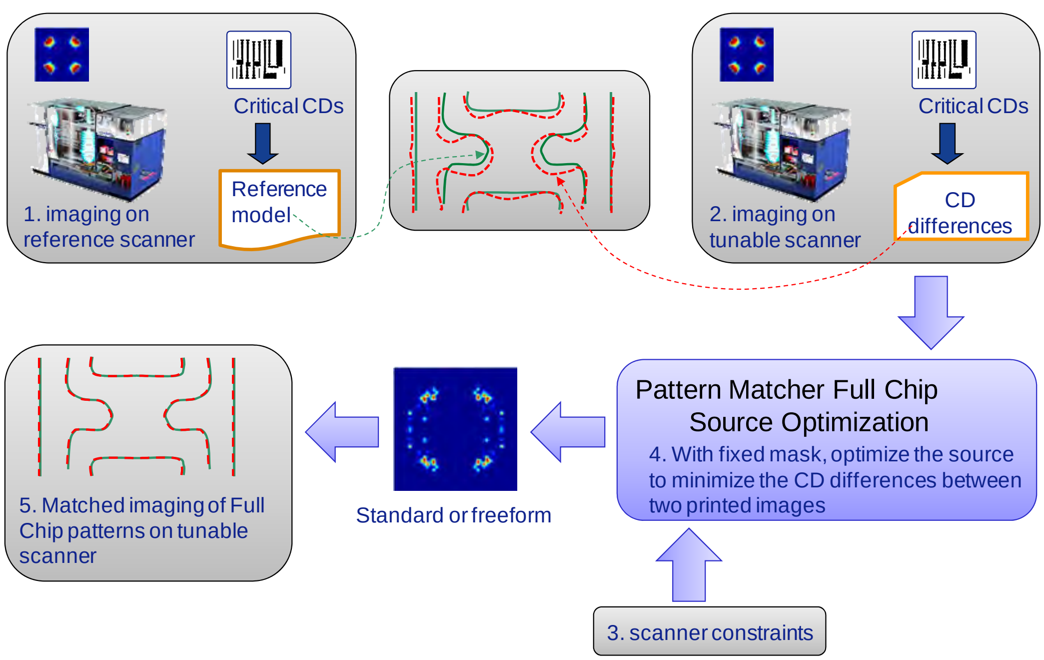

Figure 5. ASML Brion Pattern Matcher Full Chip flow for freeform source tuning.

3.2 Demonstration of freeform matching for a range of applications

In the following subsections, we investigate a number of use cases in which proximity matching could be beneficial. In each of these cases, V and H lines were measured through pitch, like above, and source tuning is applied in order to reduce the delta CD through pitch. The four use cases are the following:

- scanner to scanner variation
- reticle to reticle variation
- resist process variation
- CD target change

3.2.1 Scanner to scanner variation

In addition to the ASML XT III:1900Gi FlexRay scanner which was considered in Chapter 2, wafer exposures were performed on an XT IV:1950Hi scanner, equally equipped with FlexRay. The two tools are set up completely independent from each other, in two different fabs, and no prior matching activities took place. On both scanners, the same nominal settings were entered, fully independent from each other. Also the resist stack was nominally identical, although each exposure tool was operated with its own track (interfaced Sokudo track in the case of the XT:1900i, and off-line TEL track in the case of the XT:1950i). The same illumination settings as in the above experiments were used, printing V and H lines of ~45 nm through pitch in resist by using the same fixed pitch/bias combinations. For the matching purpose, the XT:1950i cluster was considered as reference tool, and the XT:1900i cluster as tool to-be-matched.

Figure 6 shows the experimental delta CD curves through pitch, obtained from wafer CD measurements, for four different illumination conditions. Although a particular signature is found in common for the different curves, the bulk of the delta CD values lies within ±0.8 nm. Considering that the exposure tools are independently set up, this is a very good result and further proximity matching trying to reduce the 0.8 nm is not worthwhile. The exact root cause for this small signature is not known, nor investigated, but can be understood considering that both exposure tools are from a different generation (meaning e.g. small differences in wafer stage dynamics and in lens design) and that some small differences may exist in the wafer processing (e.g. exact barc, resist, bake, development properties), as well as in the exact laser spectra.

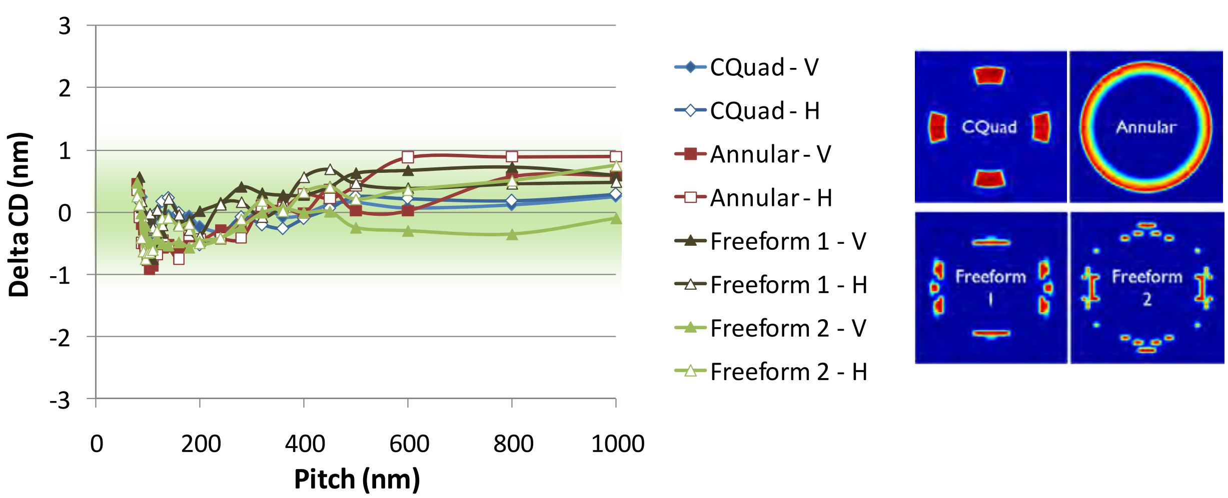

Figure 6. Match between two different and independent exposure clusters equipped with FlexRay. Experimental difference curves for four illumination conditions, obtained by subtracting the measured proximity curves on XT:1950i wafers from those measured on XT:1900i wafers.

Besides the four illumination conditions shown in Figure 6, the experiment was also conducted using dipole Y illumination at NA reduced to 1.20 (identical to above in Section 2.1). With this setting, the target in resist is 45 nm through pitch for the 'easy' horizontal lines, and 55 nm for the 'difficult' vertical lines. Note that the target of 55 nm is

still very aggressive for the vertical lines, as in practical application a rule of thumb is to multiply the target of the 'easy' direction by a factor of 1.5~2.

The experimentally obtained delta curve through pitch is depicted by the red curve 'before matching' in Figure 7. The latter shows a very good match between the two exposure clusters for the horizontal lines (delta CD ≤ 0.5 nm), but shows a CD offset up to ~5 nm for the vertical lines. This CD offset is due to the very high sensitivity of these 'difficult' features with respect to virtually all components in the imaging and patterning.

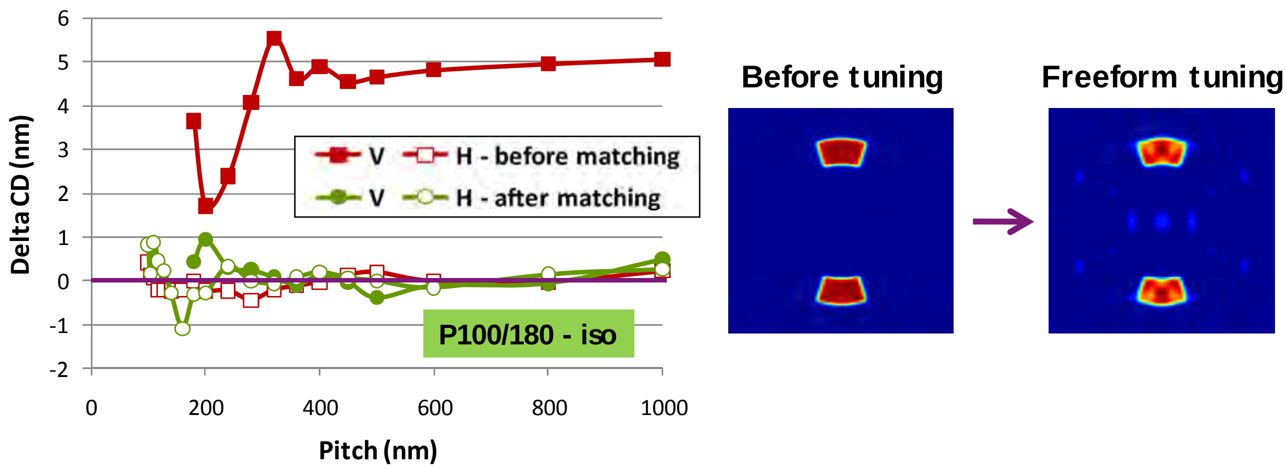

Figure 7. Experimental CD difference between two exposure clusters, for a dipole Y condition. Red curves: before matching. Green curves: after matching using freeform source tuning. Right: source image before and after tuning.

By using the freeform source tuning routine of ASML Brion's Pattern Matcher, the source was modified to the one shown at the right side in Figure 7. By uploading this calculated source onto the XT:1900i FlexRay, and measuring the proximity curve after wafer exposure using this optimized source, the delta curves through pitch are found to be close to zero. In particular, major matching improvement was found for the V lines, with very limited penalty on the H lines.

In addition to freeform tuning, the matching routine has also been used to find an optimized source based on traditional NA and sigma tuning. The outcome was a very limited change of NA (-0.01) in combination with limited change in sigma_inner (-0.005) and sigma_outer (+0.011). In agreement with what Tachyon predicted, the experimentally obtained residual delta CD curve was still very close to the original curve before tuning. This 'failure' of NA/sigma tuning for this particular example is logical, because NA & sigma tuning is not capable of affecting the V lines without affecting the H lines. Using freeform matching, however, the latter is possible, which is a very direct demonstration for the improved matching capabilities with freeform source tuning.

3.2.2 Reticle to reticle variation

While in the above example one scanner is matched to another, using the same reticle on both scanners, the following example deals with proximity matching between two different reticles. This use case may occur in practice when two scanners are used for parallel production, using two nominally identical reticles. In reality, different reticles may have a particular difference in their mean-to-target (MTT), either due to fabrication variations at a given mask shop, or due to non-matched reticle metrology at two different mask shops.

First, a short simulation study is conducted to investigate what would be the effect on wafer CD through pitch if a global CD offset exists between features patterned on two masks. I.e. we consider two virtual masks, in which all reticle CDs (hence for all features) are offset by a certain amount for one reticle compared to the other.

In such case, the effect on wafer CD originates from the interplay between:

- the mask error enhancement factor (MEEF), causing a through-pitch CD deviation from target on wafer
- the dose sensitivity, which is inversely proportional to the exposure latitude, and is used to retarget.

In the example we will study, the illumination condition is the freeform 1 source as described in Chapter 2 above. Like before, we consider regular V and H line patterns through pitch. Using KLA-Tencor PROLITH, the MEEF and dose sensitivity through pitch are simulated, and the result is shown in the left graph of Figure 8. As an example, assuming a 1.5 nm global CD offset (at 1X, wafer dimensions) between both reticles, the resulting difference curve on wafer is shown in the right graph of Figure 8. Note the characteristic fingerprint of this simulated difference curve: it shows a very steep slope at the dense side, followed by a rather flat behavior from semi-dense to isolated pitches.

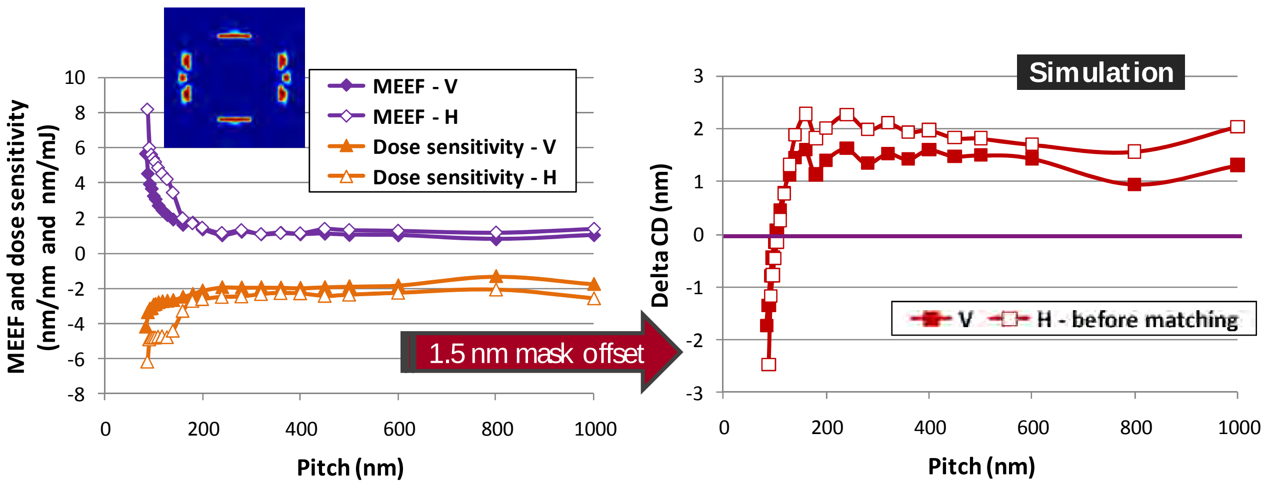

Figure 8. Left: Simulation of MEEF and sensitivity to dose for lines through pitch with given freeform source. Right: Calculated CD difference curve through pitch assuming 1.5 nm (1X) global offset between features on both masks.

The experimental difference curve as obtained from measurements on wafers exposed with two different versions of nominally the same mask is shown by the red curve in Figure 9. The characteristic fingerprint as simulated above can be recognized, indicating that these CD differences are largely explained by a global CD offset between the features on the different masks. By applying the Pattern Matcher freeform source tuning, the CD differences could be clearly reduced, from a range of over 4 nm before matching to a range of 2 nm after the freeform source tuning. It is important to note that the traditional sigma tuning is not a viable option for freeform sources, like in this example, since the sigma definition is invalid for non-parametric sources.

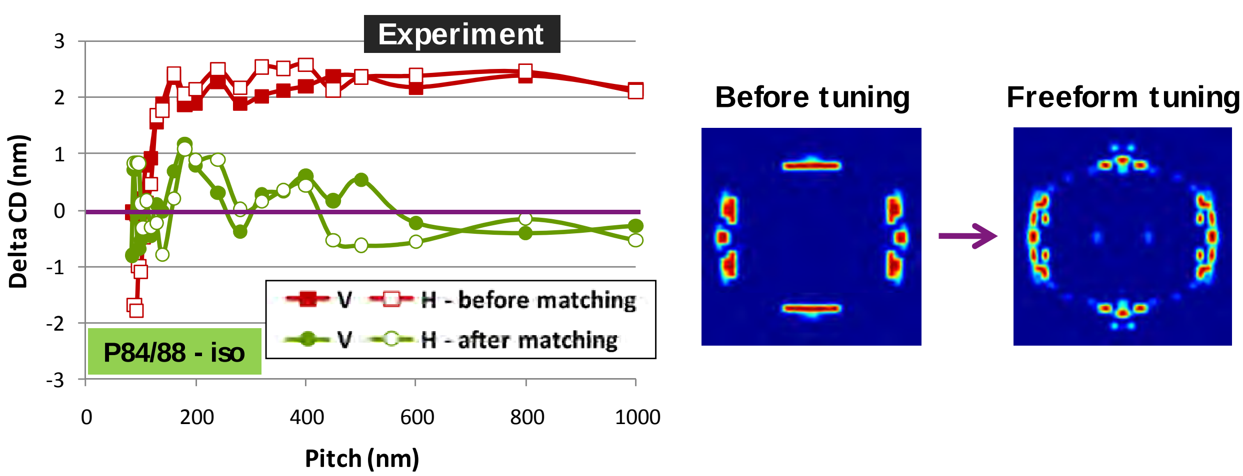

Figure 9. Left: Experimental delta CD on wafer resulting from exposure using two different masks. Red curves: before matching. Green curves: after matching using freeform source tuning. Right: source image before and after tuning.

3.2.3 Resist process variation

As a third example, we consider the use case where the difference curve originates from wafers exposed on one and the same scanner, with one and the same mask, but using different resist stack on the wafer. More in particular, the difference lies in the presence/absence of a topcoat on top of the resist. The experimentally obtained CD difference curve is shown by the red curve in Figure 10, in which the proximity curve measured on the wafer with topcoat is subtracted from that measured on the wafer without topcoat. In this example, the source used for the experiments is the freeform 2 source as described above. Also in this example, Pattern Matcher freeform tuning leads to a clear reduction of the CD mismatch, visible in a reduction by a factor of 2 in the range of the delta CD.

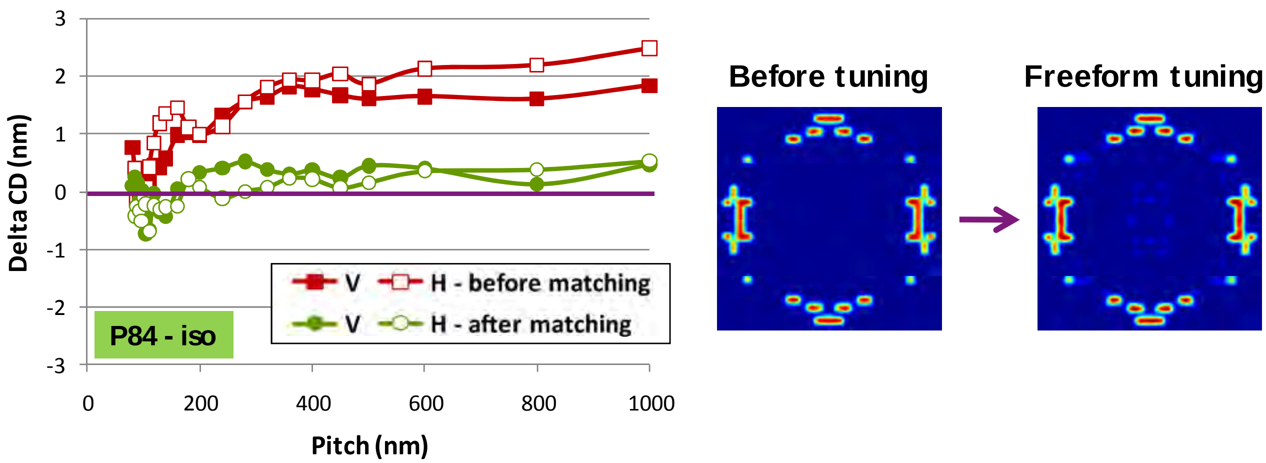

Figure 10. Experimental CD difference between wafers with and without topcoat applied. Red curves: before matching. Green curves: after matching using freeform source tuning. Right: source image before and after tuning.

3.2.4 CD target change

In a final use case, the delta CD through pitch has no physical background as it has been created with the intention of a deliberate and controlled change of the printed CD through pitch. This use case may be relevant for a situation where a mask has been manufactured, and it is desired to correct/modify a selection of specific targets without redo of OPC and mask manufacturing. To achieve this, matching towards a virtual reference can be applied.

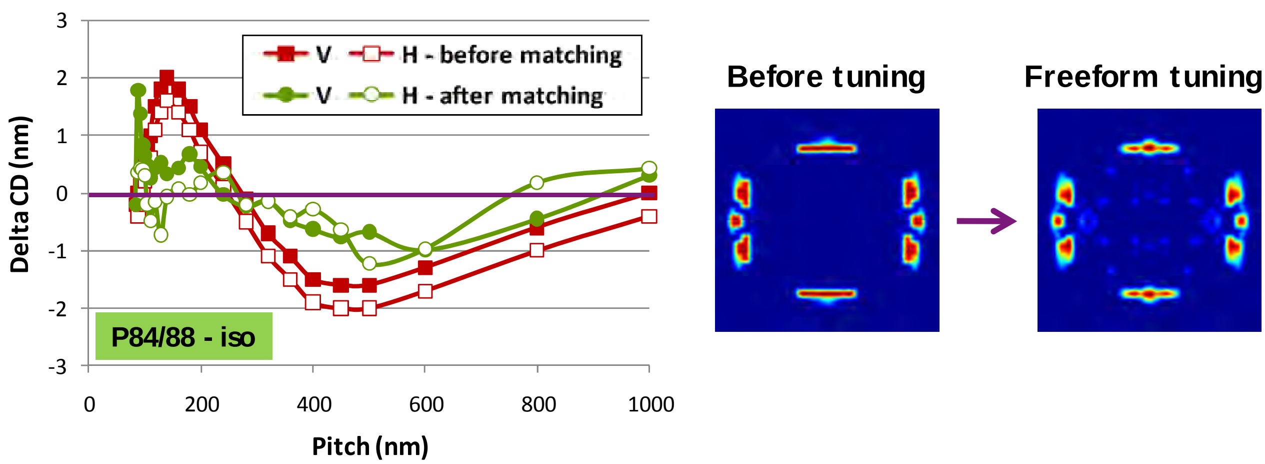

Figure 11. Application of freeform tuning for achieving a deliberate change of the printed target CD. Red curves: intended CD modification through pitch. Green curves: experimentally obtained CD modification. Right: source image before and after tuning.

The red curves in Figure 11 show the intended CD modification through pitch. We have deliberately chosen a signature through pitch which is aggressive and substantially different from the difference curves in previous use cases. The source image before and after freeform tuning is shown in Figure 11, as well as the experimentally obtained CD modification through pitch. Apart from a couple of points at the very dense side, and a residual signature through pitch, also this example demonstrates the capabilities of freeform source tuning as it has clearly improved the mismatch to the virtual reference (i.e. modified CD targets).

3.3 Impact on process window

A concern when applying proximity matching in general is the conservation of process latitudes. Indeed, enhanced CD matching by scanner tuning is acceptable only without significant penalty on the process latitudes. To investigate this, process windows have been simulated for a series of line patterns through pitch using the sources before and after tuning from the above matching exercises. For all these cases, very limited impact on process window was found. By means of example, Figure 12 shows the simulated exposure latitude (EL) and depth of focus (DoF) at 5% EL for the use case of Section 3.2.1 above, which could be considered as the case where the ‘largest’ source tuning was required. The data confirms only minor change of the process latitude.

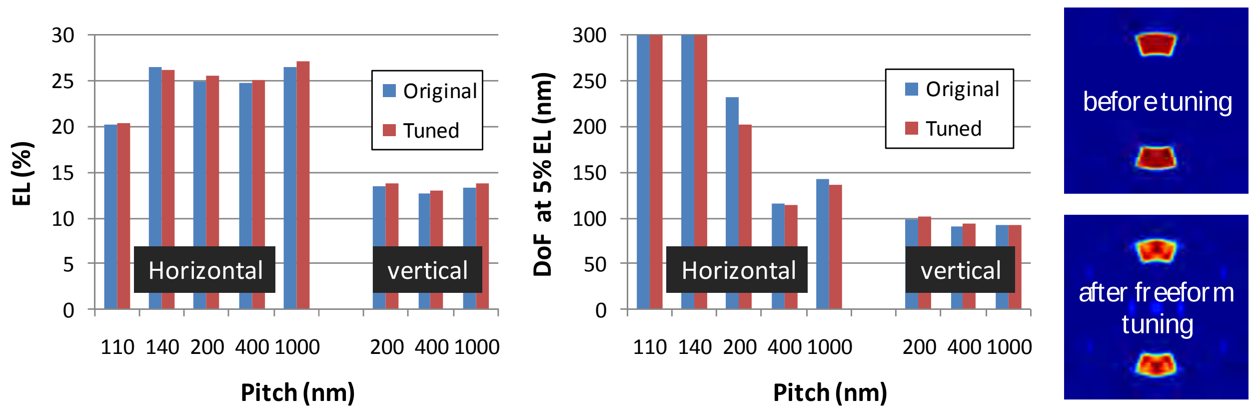

Figure 12. Impact on exposure latitude and depth of focus for the source tuning described in Section 3.2.1.

CONCLUSION

The capability to generate both traditional sources and fully freeform sources on demand, with virtually unlimited tuning potential, makes the ASML FlexRay illuminator a convenient tool for both exploratory work and production. This work demonstrated how the illuminator upgrade from the DOE based (Aerial) to the FlexRay illuminator on a given XT:1900i scanner comes without penalty in proximity on wafer (<0.5 nm), thereby providing the indispensable continuity in patterning performance with respect to earlier Aerial operation. In addition, based on regular source measurements over a 3 month period, the impact of the source variation over time was demonstrated to be at most 0.1 nm, proving the source stability.

Having the FlexRay illuminator in place opens new possibilities with respect to proximity matching. Indeed, while the traditional sigma tuning has only limited degrees of freedom, the possibility of freeform source tuning enhances the matching capabilities. Complementary to this, the use of ASML Brion’s Pattern Matcher software provides a computational routine to determine the optimally tuned source. By means of different use cases, the benefit of freeform source tuning for proximity matching has been demonstrated. In particular, solutions have been provided for situations where traditional NA and sigma tuning appeared insufficient, or situations in which the source to be tuned is already freeform and therefore sigma tuning is not applicable.

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